PHOSPHORUS REMOVAL

BY

LIME ADDITION

TO A

CONVENTIONAL ACTIVATED SLUDGE

PLANT

THE ONTARIO WATER RESOURCES COMMISSION

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By

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ABSTRACT

It has been generally accepted that phosphorus is the nutrient most likely to be limiting to algal growth in our fresh-water lakes. Several agencies have therefore proposed that phosphorus removal be incorporated into sewage treatment processes in an attempt to curb the rate of eutrophication of receiving waters.

Many process modifications have been investigated throughout the world as possible methods of removing phosphorus from domestic sewage, the most promising of which involve the addition of chemicals to cause the precipitation of the various forms of phosphorus in sewage. The most extensively studied processes have involved the addition of chemicals to activated sludge effluent as a tertiary stage. Such processes however, require the duplication of existing facilities and in general, require relatively high dosages of chemicals, as with most chemicals, the required dosage increases exponentially with decreasing phosphorus residual.

The Division of Research, OWRC initiated studies on the chemical removal of phosphorus early in 1965, working towards an economical method of modifying an existing conventional activated sludge sewage treatment plant to include a phosphorus removal process.

Following extensive laboratory jar test and model scale studies, a full scale investigation was begun in January of 1969 on the 180,000 IGPD section of the Richmond Hill WPCP. In this study, hydrated lime was added to the raw sewage influent channel to the primary clarifier at an average concentration of 175 ppm with chemical flocculation and sedimentation taking place within the primary clarifier. The primary effluent then passed on through the secondary process.

Sampling before and during lime addition indicated, that as well as effecting high degrees of phosphorus removal, the lime addition resulted in greatly improving the Biochemical Oxygen Demand and Suspended Solids removals of the entire process.

Although further investigation is required to establish additional process refinements, this study demonstrated that phosphorus removal can be effectively implemented at an existing conventional activated sludge plant at a reasonable cost which is offset considerably by treatment and increased capacity benefits.
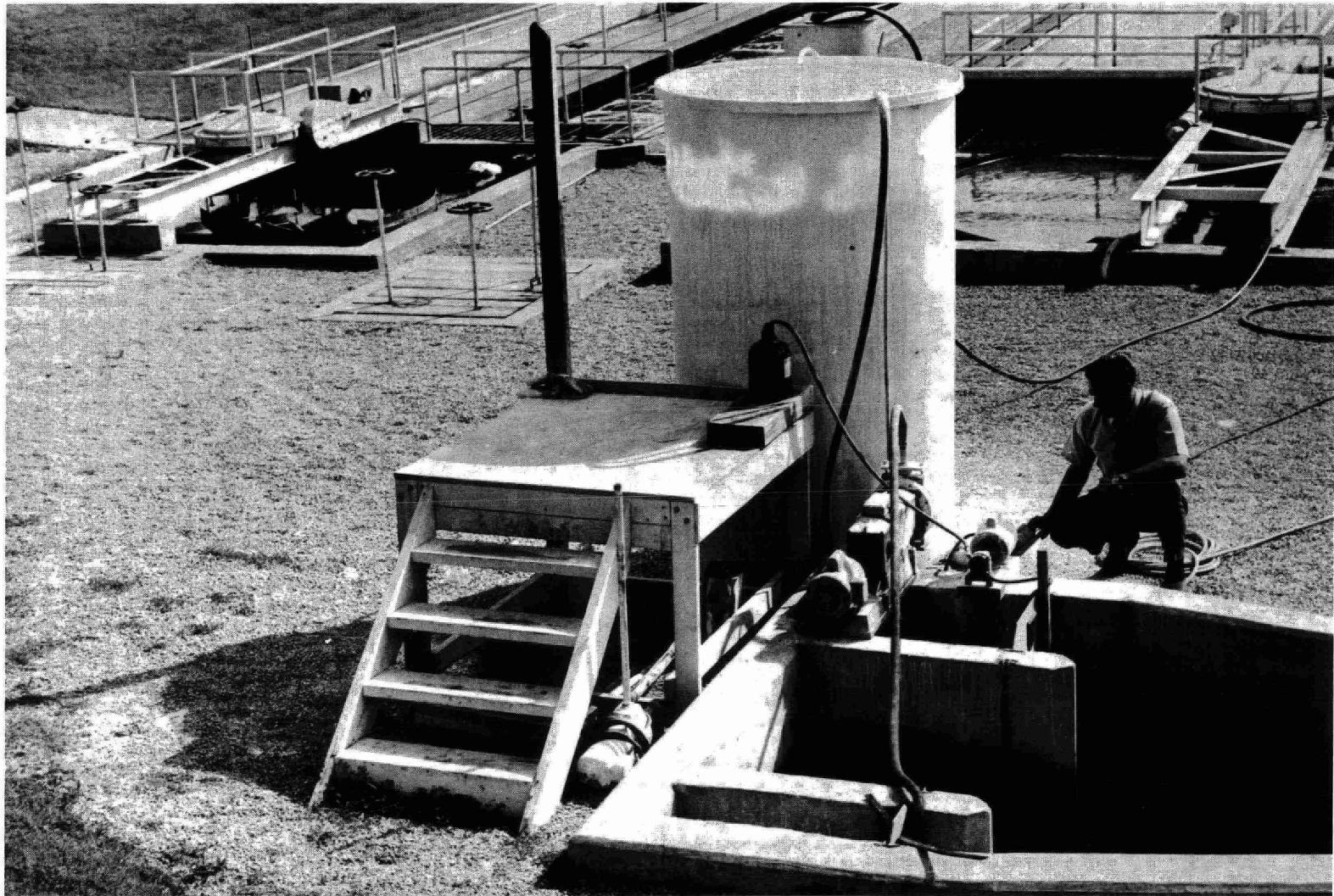
PHOTOGRAPH OF LIME FEED EQUIPMENT
RICHMOND HILL WPCP DEMONSTRATION PROJECT

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1.0 INTRODUCTION

It has been recognized for some time that 5-Day Biochemical Oxygen Demand (BOD) and Suspended Solids (SS) are inadequate measures of the efficiency of sewage treatment when assessing the effects of waste effluents on receiving waters. Recently, emphasis has been focused on nutrients, namely phosphorus, nitrogen and carbon, and their relationships to receiving water eutrophication.

Although considerable controversy still exists over the relative importance of the above nutrients, phosphorus has been generally accepted as the nutrient most likely to be limiting to algal growth in lakes and other water impoundments. Nitrogen is considered to be limiting in streams and fast flowing waters, while carbon may become limiting in certain soft-water lakes.

Accepting the above theory and because of the vast interconnections within our waterways, phosphorus removal should be considered for all sewage treatment processes. Nitrogen and carbon removal requirements will be dictated by specific receiving water conditions and BOD criteria should be such as to not cause any oxygen deficiency within the receiving water. Suspended Solids removal objectives should not be relaxed from the present level.

Phosphorus is present in sewage in three groups of compounds: as orthophosphates, as bound phosphorus in organic compounds, and as polyphosphates of either industrial or biological origin. Orthophosphate makes up about 50-60% of the total phosphorus in settled raw sewage; biological treatment by hydrolyzing the polyphosphates to orthophosphates shifts this proportion to about 80-85% in the final effluent. Any phosphorus removal process must therefore consider all compounds of phosphorus.

In the conventional activated sludge process, phosphorus is removed during both primary sedimentation and biological treatment. Primary sedimentation in physically settling out the heavier solids, removes that part of the phosphorus contained in these solids. Phosphorus removals in the order to 5 to 15% are so achieved although more efficient primary sedimentation could increase these removals to more than 30%.

Since phosphorus is an essential element to all life processes, some removal is effected by the activated sludge process through its incorporation into biological sludge. Removals of total phosphorus are generally limited to 20 to 50%, although a large percentage of the more complex polyphosphates are reduced to soluble orthophosphates.

Although several writers (Lea and Nichols, 1936; Sawyer, 1944; Wuhrmann, 1957; Bogan, 1961) have reported on the improbability of using the activated sludge process for high degrees of phosphorus removal, other writers (Harris, 1957; Srinath et al, 1959, Alarcon, 1961; Feng, 1962) found that many microorganisms are capable of taking up phosphorus in excess of their requirements. Shapiro and Levin (1965) investigated this possibility within the activated sludge process while Vacker, et al (1967) reported on this phenomenon at the San Antonio, Texas WPCP. Shapiro and Levin indicated that 75% removal of the phosphate normally present in activated sludge effluents was possible through plant and process modifications. Vacker, et al, reported on phosphate removal efficiencies as high as 96% although they failed to be entirely convincing in the mechanism by which this removal occurred (Jenkins and Menar, 1968). In any event, in view of the high removal levels of phosphorus required, the use of such biological process modifications, in spite of their inherent economic advantages, requires further investigation before their widespread application at existing sewage treatment plants.

Presently proposed phosphate removal processes are generally based on the chemical precipitation of phosphates where a) the orthophosphates are precipitated as insoluble salts of metallic cations such as Fe^{+3}, Al^{+3}, Ca^{+2} and b) the organic and polyphosphates are adsorbed onto the hydroxide floc of these metals.

Chemical treatment for phosphorus removal may involve a) chemical treatment of raw sewage, b) chemical treatment of activated sludge effluent, or c) combined chemical-biological processes.

1.1 Combined Chemical-Biological Processes

These processes involve the addition of minerals directly into the aeration tank of the activated sludge process

resulting in the formation and precipitation of slightly
soluble phosphorus compounds. Additions such as aluminum or
iron salts are commonly used with mixing provided by the
aerators and by allowing sufficient opportunity for floc
formation. The combined chemical-biological process has been
studied by many investigators on laboratory and pilot scale
processes.

Perhaps the most extensive study of the combined
process was carried out by Eberhardt and Nesbitt (1968) when
they investigated chemical precipitation of phosphorus within
the high rate activated sludge process, using aluminum sulfate.
They concluded from their results that essentially complete
soluble phosphorus removals are attainable by the combined
chemical-biological process. Similar conclusions have been
drawn by other investigators (Tenney and Stumm, 1965; Ericsson
and Westberg, 1966; Thomass, 1966; Wuhrmann, 1968). The period
of continuous operation in each of these cases however, was less
than 4 weeks. More recent work by Popel (1968) and Bebin (1968)
has indicated that under prolonged operation of the combined
chemical-biological process, deterioration of treatment quality
as measured by BOD and SS content of the effluent occurred
following an increase in non-volatile solids within the system.
A reexamination of the data by Eberhardt and Nesbitt indicates
an increasing concentration of non-volatile or chemical content
in the waste sludge until the termination of the test run.
Perhaps they too would have experienced a loss of biological
floc had they continued their test run.

Further research into the combined chemical-
biological process is warranted before such processes are placed
into widespread use although such processes show definite pro-
mise and involve no duplication of facilities.

1.2   Chemical Treatment of Activated Sludge Effluent

These processes, often classed as tertiary treat-
ment processes, involve the removal of phosphorus from an
activated sludge effluent through precipitation by ferric or
aluminum salts or by the alkaline precipitation of phosphorus
with lime or with combinations of lime and ferric salts.

Most of the investigations on the removal of

phosphorus from wastewaters have concerned this type of process
and have been found to be both effective and economically feas-
ible. Several full scale installations are presently in
operation throughout the world, ranging in capacity from less
than 0.3 mgd to greater than 7.5 mgd (Weinberger, 1968).

The classic example of phosphorus removal as a tertiary
step is the Lake Tahoe installation (Culp & Mayer, 1969). Phos-
phorus is removed here by the addition of 400 ppm of lime as
CaO (530 ppm as $Ca(OH)_2$) from the final effluent of the $7\frac{1}{2}$ mgd
South Lake Tahoe activated sludge process.

Phosphorus removal as a tertiary process however, re-
quires the duplication of facilities already available at the
secondary sewage treatment plant. Flash mixing, chemical
storage and feeding equipment as well as extra flocculation
and sedimentation basins are required necessitating substan-
tial initial investment in addition to the capital cost of the
secondary process. Large dosages of chemicals are also re-
quired resulting in high chemical costs and large quantities
of voluminous sludge.

1.3   Chemical Treatment of Raw Sewage

The final choice for phosphorus removal involves the
addition of chemicals to the influent of the primary clarifier
of the activated sludge plant or of the primary treatment
plant. The chemicals used and the reactions involved are
similar to those of the tertiary treatment process but the
effectiveness of the chemical is greatly enhanced. In any
chemical process for phosphorus removal, the amount of pre-
cipitant or coagulant required is dependent upon the allowable
concentration of phosphorus in the effluent; in general, the
amount of chemical required increases exponentially with de-
creasing phosphorus residual. The bacteria in activated sludge
however, can readily utilize phosphorus at very low concen-
trations. Therefore, by preceding the activated sludge process,
chemical treatment can remove the bulk of the phosphorus with
biological growth removing much of the remaining portion.

Additional equipment requirements for installing this
type of process at an existing activated sludge or primary
plant would include chemical storage, feeding and control
equipment. The existing primary clarifier however, may be

used for the chemical flocculation and sedimentation steps.
Depending upon plant design, flash mixing and/or additional
sludge handling facilities may also be required.

As early as 1952, staff of a division of the Ontario
Department of Health which was later incorporated into the
OWRC, realized the benefits of lime waste on the activated
sludge process and a study was carried out at Aurora to deter-
mine the effects of spent lime liquor from a tannery, on the
activated sludge plant for that town. Although phosphorus
removal was not considered in sewage treatment at that time,
recent analyses on a series of samples have determined an
average 88% phosphorus removal at that plant which has been
attributed to the lime waste addition.

Recently, considerable emphasis has been placed on
the chemical treatment of raw sewage for phosphorus removal
by other agencies and organizations as well. Sawyer (1966)
proposed a phosphorus removal scheme of this nature employing
lime treatment of raw sewage followed by either oxidation pond
or activated sludge treatment. Dorr-Oliver Ltd. (1967) have
proposed a similar process, the Phosphate Extraction Process,
again employing lime treatment of raw sewage followed by con-
ventional activated sludge treatment. Most recently Schmid and
McKinney (1969) have proposed the same type of treatment, all
with varying modifications. The studies on which these pro-
cesses have been based however, were conducted as jar tests
and to our knowledge, none have been carried out on a full
scale treatment facility.

Although this report concerns a field scale investi-
gation of such a process, no claim is made that this is a
technological invention. It is rather, a revised application
of processes that have been known for years, to effect a new
objective, that of phosphorus removal. To our knowledge, it
is the first time this process has been applied on a field
scale, designed specifically for the removal of phosphorus.

Historically, the chemical treatment of sewage is one
of the earliest processes of sewage treatment and was used ex-
tensively in England between 1880 and 1890 and again in the
United States in the 1930's and early 1940's. Chemicals used,
either alone or in combination, included alum, lime, copperas,
ferric sulphate, ferrous chloride and ferric chloride.

The decline in chemical treatment processes was due to the development of biological processes that secured better results at a lower cost. Its revived interest in recent years may be attributed partially to the increased availability of chemicals, better knowledge of the chemistry of the process, and improved methods of handling the sludge produced. To date, chemical process methods have been found to be the only consistently adequate means of removing phosphorus from municipal wastes.

2.0   LABORATORY INVESTIGATIONS

The Division of Research, OWRC, became involved with phosphorus removal processes early in 1963. Research was originally directed toward the utilization of phosphorus by algae and subsequent harvesting of the algal growth. Under Ontario's climatic conditions however, it was found that phosphorus removals in this manner were highly inconsistent (OWRC, Research Paper No. 2004) and the decision was made to investigate chemical process methods.

Laboratory jar tests on wastes from various municipalities were used to determine which of the many coagulants and precipitants were most effective in removing phosphorus from sewage. Investigations simulating various process modifications also determined chemical treatment of raw sewage to be the most economical method for its removal.

As lime and combinations of lime and ferric chloride showed the greatest promise in the jar tests, the use of these chemicals was further investigated in a continuous flow model primary treatment plant as depicted in Figure 1.

The model plant process consists basically of combined flocculation and settling zones to allow for rapid return and intimate mixing of the chemical sludge with the influent raw sewage mixture. Lime and raw sewage are fed into a flash mixing chamber which overflows into the mechanically mixed flocculation zone. When ferric chloride is used it is added at this point. The flocculated sludge then passes into the settling section with a high percentage of the settled sludge being returned to the flocculation zone by gravity and the mixing flow patterns within the flocculation zone. Before passing over the effluent weir of the settling section, the liquid must first pass through the chemical sludge within the settling zone thereby improving its clarification.

From these laboratory investigations, combinations of lime and ferric chloride were found to produce optimum phosphorus removal efficiencies where the plant process is limited to chemical treatment alone. For the conventional activated sludge process where secondary treatment follows primary treatment, additions of lime alone, to the primary clarifier, produced optimum results.
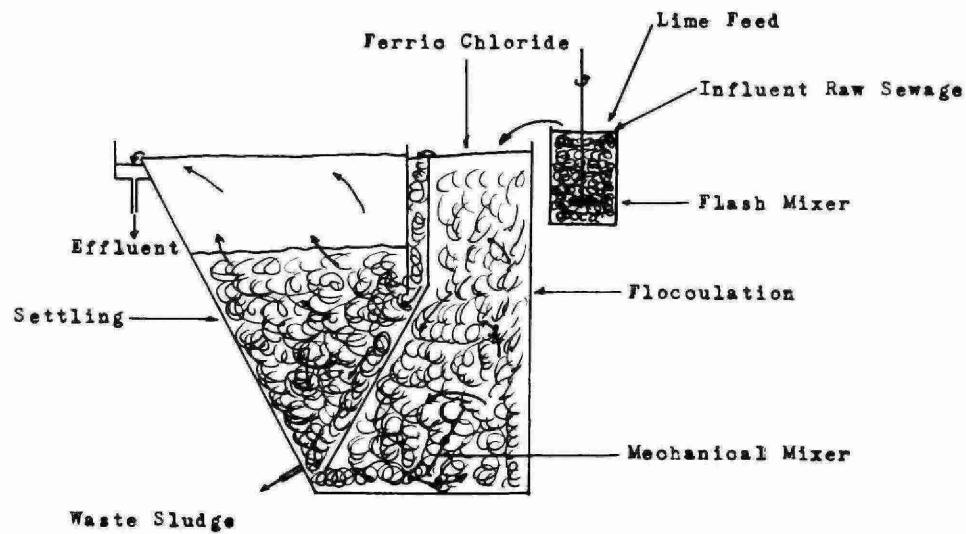
Ferric Chloride

Lime Feed

Influent Raw Sewage

Flash Mixer

Effluent

Flocculation

Settling

Mechanical Mixer

Waste Sludge

Table 1 presents typical effluents of the model chemical treatment plant using (1) a combination of lime and ferric chloride such as could be used for the complete treatment of sewage and (2) lime addition alone, such as would be used for the removal of phosphorus in the primary clarifier of the conventional activated sludge plant. It should be noted that a different sewage source was used in these laboratory studies than that of the field scale studies.

TABLE 1

Pilot Plant Data

(Chemical Treatment Only)

(1) Chemical Addition - 250 ppm Lime, 5 ppm $FeCl_3$

	BOD ppm	SS ppm	COD ppm	Nitrogen* ppm as N	Total P ppm as P	Ortho P ppm as P
Influent	220	371	692	76	14	8
Effluent	36	5	95	34	0.4	0.1
% Reduction	84	99	86	55	97	99

Averages of 8 weeks continuous flow data

(2) Chemical Addition- 210 ppm lime

	BOD ppm	SS ppm	COD ppm	Nitrogen* ppm as N	Total P ppm as P	Ortho P ppm as P
Influent	212	342	586	71	14	9
Effluent	40	8	98	33	1.2	0.8
% Reduction	81	98	83	54	91	91

Averages of 10 weeks continuous flow data

* Total Kjeldahl Nitrogen

PHOTOGRAPH OF PRIMARY CLARIFIER

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3.0 <u>FIELD STUDIES</u>

At the completion of these laboratory studies it
was decided that the chemical treatment process was at a stage
such that a field-scale experiment at an operating plant would
be feasible. Studies were therefore initiated at the Richmond
Hill WPCP early in April of 1969.

3.1 <u>Plant Description</u>

The Richmond Hill WPCP consists of three activated
sludge treatment units in parallel with common influent works
and sludge treatment units. The first stage, built in 1951,
consisted of a primary clarifier, 2 aeration tanks, a secondary
clarifier, a digester and sludge drying beds, and was designed
at 180,000 IGPD capacity. Additions of parallel plants were
made in 1956 and in 1957 giving a total design capacity of
1,635,000 gallons of sewage per day.

For purposes of this study, the primary clarifier,
aeration tanks and secondary clarifier of the original plant,
were completely isolated from the other two sections. These
units only, will be described in detail.

A line diagram of the Richmond Hill WPCP as it pre-
sently exists is presented in the appendix to this report.
The test section has been shaded in. It should be noted that,
as mentioned in a later section of this report, the common
sludge return facilities for sections 1 and 2 were modified
such that each section was completely isolated from the other
in this regard.

a) Primary Clarifier - The primary clarifier has a diameter
    of 16 feet and a side water depth of 10 feet giving a
    volume of 2,010 cu ft or 12,550 gals. and a detention
    time of 1.68 hours at design flow. The primary clarifier
    provides a surface settling rate of 900 gal/sq ft/day and
    a weir overflow rate of 4,880 gal/lin ft/day at design
    loading.

b) Aeration Tanks - The aeration section consists of two
    tanks 58 ft x 9 ft x 9 ft liquid depth giving 4,700 cu
    ft each or 58,600 gals total capacity providing an

aeration detention of 7.8 hours at design flow excluding return sludge.

c)   Secondary Clarifier - The original plant included one circular final clarifier of 19 ft diameter with a 10 ft liquid depth providing a detention of 2,835 cu ft or 17,680 gals and 2.35 hours at design flow. The secondary clarifier provides a surface settling rate of 635 gal/sq ft/day and a weir overflow rate of approximately 4,000 gal/lin ft/day.

d)   Plant Modification for Study - For study purposes a pump had to be provided for returning secondary sludge to the aeration process because common facilities had been provided for the two adjacent sections. As it was important to determine daily flow rates through the plant under study, the primary weir overflow channel was dammed and a V-notch weir and flow chart recorded installed. Other than these two physical modifications the only other changes made involved plant operation, i.e. flow stabilization, air supply, sludge withdrawal, etc.

It should be noted that primary sludge withdrawal facilities are common to all three plant sections and it was difficult to obtain accurate measurements of sludge production in the test section. It is felt, nevertheless, that samples and production values were representative.

3.2 Study Approach

The entire study was kept as simple as possible in order that the results obtained under these test conditions would be improved in a full scale treatment process with more sophisticated equipment. Elaborate sampling and analytical procedures were carried out to obtain the maximum information possible from the study.

For two weeks prior to the actual chemical addition, background information was collected across the entire test section of the plant at its design capacity. Although the data collected over this two week period will be presented in a following section, it should be noted here that these data are not necessarily representative of the entire plant process.

The test section is the oldest and smallest of the three plant
sections and at the time of the study, even under design flow
conditions, was producing the poorest effluent.

A concurrent sampling program on the adjacent section
indicated that it could not be used as a comparison for the
treatment modifications as treatment efficiencies differed
widely between the two sections.

As the main purpose of this study was to determine
the practicability of employing a chemical treatment process
for phosphorus removal at an operating activated sludge plant,
it was not felt that a parallel process comparison was re-
quired so no further attempt was made in this regard.

For the chemical addition studies, a commercial
grade of hydrated lime was mixed in a 500 gallon plastic drum
to a concentration of 10% by weight. The contents were kept
well mixed by blowing air into the bottom of the drum even
though it was realized this air could reduce the efficiency
of the lime through its partial carbonation. No other simple
method of mixing was available. The lime mixture was metered
out with a "Lapp Pulsafeeder" pump with a possible flow rate
variation of from 0 to 40 gph.

Laboratory jar tests had indicated that approxi-
mately 200 ppm of lime were required to effectively reduce
the total phosphorus level to below 1.5 ppm as P. It was also
determined that at this lime dosage, the resultant pH was 9.3.
This left two avenues open for controlling lime feed control
rate. Lime feed could be proportional to the flow or it could
be controlled such that the optimum pH of 9.3 was maintained.
Since the chemical feeder which was available for this study
could be neither flow nor pH controlled, the lime feed rate
was manually adjusted in an attempt to maintain the desired
pH in the primary clarifier effluent.

Lime addition to the primary clarifier on a continu-
ous basis was begun on June 17, 1969, and continued until August
21, 1969 for a total period of 9½ weeks or 66 days. Lime addi-
tion was then discontinued for 2 weeks, restarted on September
4, 1969 and continued for an additional four weeks. Figure 2
presents a line diagram of the process as investigated at
Richmond Hill.

Lime

Raw
Sewage

Pri.
Sed.

Aeration

Aeration

Final
Sed.

Effluent

Return Activated Sludge

Sludge
Withdrawal
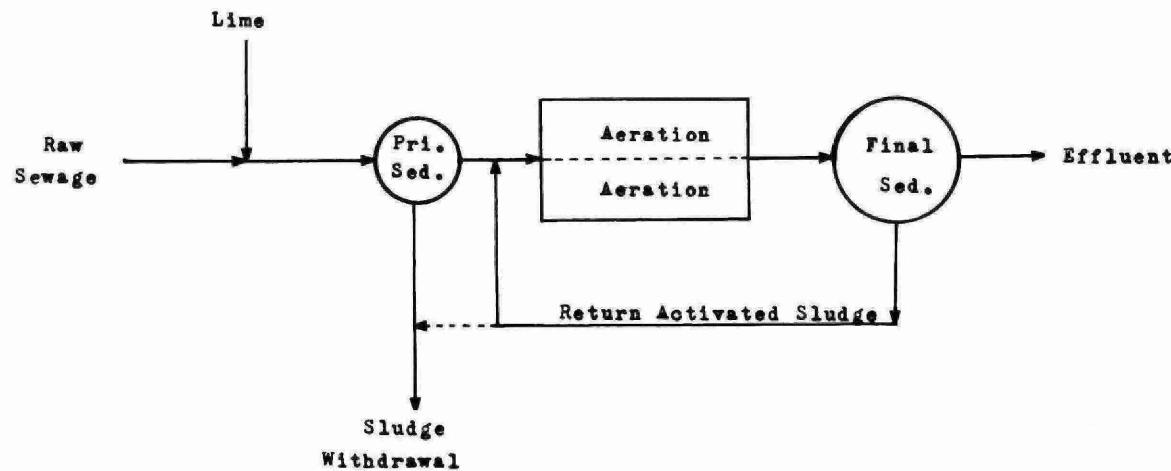
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FIGURE 2

Demonstration Plant Process

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3.3   Sampling Procedure and Tests Performed

Daily 24-hour composite samples were collected of raw sewage, primary effluent and secondary effluent, and grab samples were taken of aeration mixed-liquor and return activated sludge, throughout the entire study period. Periodic grab samples of primary sludge were also collected.

Forty-ounce bottles of 24-hour composite samples of raw sewage and primary and secondary effluents were submitted to the Laboratories for analyses for:

   a)   5-Day Biochemical Oxygen Demand,
   b)   Chemical Oxygen Demand,
   c)   Total, Suspended, Dissolved and Volatile
         Suspended Solids,
   d)   Free Ammonia,
   e)   Total Kjeldahl Nitrogen,
   f)   Nitrite and Nitrate Nitrogen,
   g)   Ortho and Total Phosphorus,
   h)   Hardness,
   i)   Alkalinity.

Routine analyses carried out at the Laboratories, on aeration mixed liquor, return activated sludge and primary sludge included:

   a)   Total, Suspended, Dissolved and Volatile
         Suspended Solids,
   b)   Ortho and Total Phosphorus.

On site determinations consisted of:

   a)   Continuous flow records,
   b)   pH determinations of all samples collected and
         grab checks on primary effluent,
   c)   Dissolved oxygen measurements at the head,
         centre and end of the aeration tanks and of the
         secondary effluent,
   d)   Aeration mixed liquor respiration rate,
   e)   Morning and afternoon determinations of
         aeration mixed liquor settling rate.

Periodic determinations of orthophosphate were also made of the raw sewage and primary and secondary effluents as well as periodic measurements of waste primary sludge volumes.

3.4 Field Results

A summary of much of the analytical data obtained from this study is presented in Tables 2 and 3 and in Figures 5 to 8. The tables present maximum, minimum and average values as well as percent reductions of various parameters while the figures present time graphs of the more significant of these parameters.

As this was the first field scale study of this process there were many techniques to be learned and mechanical adjustments to be made. Since these factors influenced the process adjustment period, the accompanying tables do not include the data obtained during the first 5 weeks of the continuous lime addition study. The graphs however, include data for the entire 9½ weeks.

As can be seen from Table 2, treatment before lime addition was relatively poor compared to that expected from a conventional activated sludge process. High storm water infiltration was perhaps the main reason for this apparent poor treatment.

The Richmond Hill Plant has a design capacity of 1.6 MIGD but the actual flows exceed this value over 75% of the time. Flows exceeding a rate of approximately 3 MIGD are bypassed to the chlorine contact chamber and although the test section was controlled as nearly as possible to design flow, flows to the contact chamber were at times so great, that the sewage backed up, flooding all three of the final clarifiers making consistent good treatment impossible.

Another reason for not including the data of the first five weeks of the lime addition study in Table 3 is that during this period, flows to the plant fluctuated greatly making the lime feed rate very critical. As adequate feed control equipment was not available for this study, it was not possible to maintain the lime feed exactly proportional to the flow and poor phosphorus removal at times resulted.

TABLE 2

Treatment Data Prior to Chemical Addition

	BOD	COD	SS	Phosphorus		Nitrogen			Hardness	Alkalinity
				Tot. P	Ortho P	NH_3	Tot. Kj*	NO_3		
Raw Sewage										
Avg.	126	353	163	10.6	6.1	18	33	0.2	412	387
Max.	320	680	490	21.4	15.2					
Min.	67	138	102	4.2	1.4					
Primary Effluent										
Avg.	99	234	102	7.9	4.1	14	30	0.1	413	362
Max.	160	333	160	11.5	6.9					
Min.	70	170	50	5.2	3.0					
Final Effluent										
Avg.	53	156	77	6.5	3.6	15	22	0.6	413	342
Max.	65	230	100	9.2	4.9					
Min.	32	105	45	2.8	1.5					
Percent Reductions										
Primary	21	34	37	25	33	22	9	50		
Secondary	46	33	24	18	12	–	27	–		
Overall	58	56	53	39	41	17	33	–		

* Total Kjeldahl Nitrogen

TABLE 3

Treatment Data During Chemical Addition

	BOD	COD	SS	Phosphorus		Nitrogen			Hardness	Alkalinity
				Tot. P	Ortho P	NH_3	Tot. Kj.	NO_3		
Raw Sewage										
Avg.	139	408	221	10.7	6.3	18	33	0.12	401	381
Max.	250	690	520	15.0	14.0					
Min.	70	159	120	6.0	1.6					
Primary Effluent										
Avg.	40	113	50	1.8	1.2	13	24	0.03	306	287
Max.	80	150	135	3.0	2.2					
Min.	22	70	20	0.6	0.3					
Final Effluent										
Avg.	5	26	5	0.9	0.5	0.5	1.2	16	377	222
Max.	9	50	10	2.0	1.8					
Min.	2	12	5	0.2	0.1					
Percent Reduction										
Primary	71	72	77	83	81	28	27			
Secondary	88	77	90	50	55	96	95			
Overall	96	94	98	92	92	97	96			

It is felt however, that with proper feed control equipment, flow variations will cause less of an upset with this process than with the conventional process. For this study, lime feed was decreased at night and increased again during the day but this was the only proportioning method used.

a) Raw Sewage

The Richmond Hill raw sewage is typical of that of a town of 20,000 population with some light industry, except for the infiltration which considerably weakened the sewage strength at periods of heavy rainfall, thereby lowering the average value. The raw sewage strength averaged 139 ppm BOD and 221 ppm SS but during dry periods these averages increased to 230 and 320, respectively.

The phosphorus content of the raw sewage is typical of that of the industrialized zone of Southern Ontario averaging 10.7 ppm as P. This corresponds to a per capita contribution of 3.5 lb/year assuming a total flow of 700 million gallons per year through the plant. Raw sewage characteristics are presented in the accompanying tables and figures.

b) Primary Performance

The primary clarifier is the focal point of this phosphorus removal process. It is here that coagulation and settling of the lime-raw sewage mixture takes place resulting in the precipitation of the bulk of the phosphorus and a large percentage of the raw sewage BOD and SS.

Prior to lime addition, the primary clarifier was giving poor treatment. BOD and SS removals were only 21 and 37% respectively, compared to the 38 and 57% reductions normally expected in primary treatment (WPCF, 1959). Total phosphorus reductions averaged 25% for the two week period.

Lime addition to the raw sewage increased the BOD and SS reductions within the primary to 72 and 78% respectively, while total phosphorus reductions were increased to 82%. Orthophosphate reductions averaged 84%. The lime addition therefore, not only greatly improved the phosphorus removal within the primary clarifier, but also resulted in an effluent much lower in organic solids, reducing appreciably the organic load on the secondary process.

Laboratory jar tests on the Richmond Hill sewage had determined that in order to obtain a residual of no greater than 1.5 ppm total phosphorus, 200 ppm of lime had to be added to the raw sewage. This resulted in a pH value of the mixture of 9.3 (Figure 3). Under field conditions, probably due to the influence of the settled lime sludge, it was found that a lime dosage of 175 ppm was adequate to obtain the required pH value of 9.3. Due to inadequacies in mixing and coagulation however, the actual primary effluent phosphorus averaged slightly above the laboratory jar test value of 1.5 ppm. The degree of mixing has little effect on the resultant pH. The importance of duplicating field mixing conditions in the laboratory tests becomes apparent from Figure 4. These graphs were obtained by varying the flash mixing and coagulation times, but in each case with a total detention period of 1 hour. Additional settling times produced insignificant removals. Field conditions were estimated as providing 2.5 minutes flash mixing and 10 minutes coagulation or slow mixing. It was found that the flash mixing became the critical factor at periods of less than 3 minutes. Optimum mixing was considered to be 3 to 5 minutes flash mixing followed by 15 minutes slow mixing.

Throughout the study, calcium carbonate accumulated on the effluent weirs and outlet troughs of the primary clarifier but these accumulations were easily removed with a water hose. There was no appreciable buildup on submerged structures within the primary.

The non-volatile suspended solids content of the primary effluent during chemical treatment averaged 38 ppm compared to 34 ppm prior to chemical treatment. The non-volatile dissolved solids contents averaged 597 ppm and 736 ppm respectively, for these two periods. This would indicate only a slight particulate lime carryover with a considerable decrease in dissolved solids carryover due to the chemical treatment. It should be noted from Table 3, that alkalinity and hardness were both reduced by the lime treatment process.

c) Secondary Process Performance

Prior to chemical treatment the aeration process was carrying a mixed liquor suspended solids content of about 2,200 ppm. Shortly following the addition of lime to the primary and because of the reduced organic loading, this solids
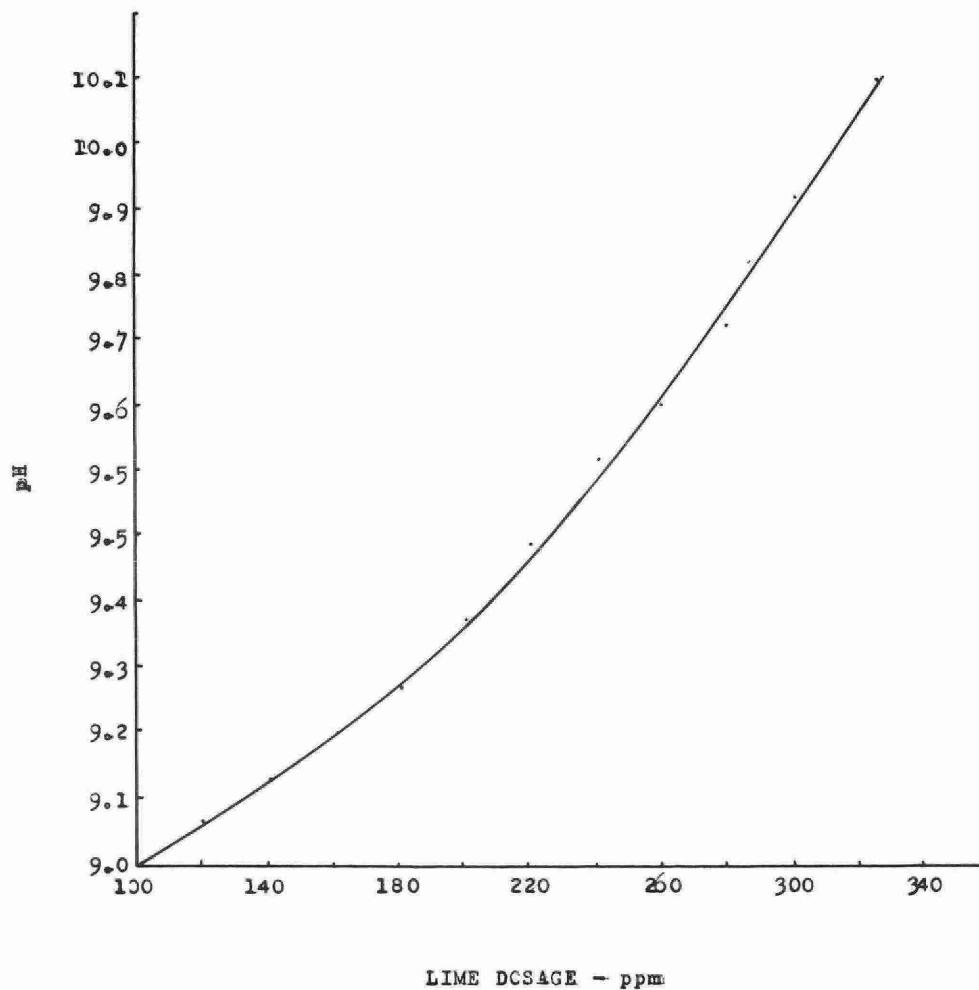
pH

LIME DOSAGE – ppm

TOTAL PHOSPHORUS REMAINING – ppm

LIME DOSAGE – ppm

Inadequate Mixing

Estimated Field Conditions

Optimum Mixing
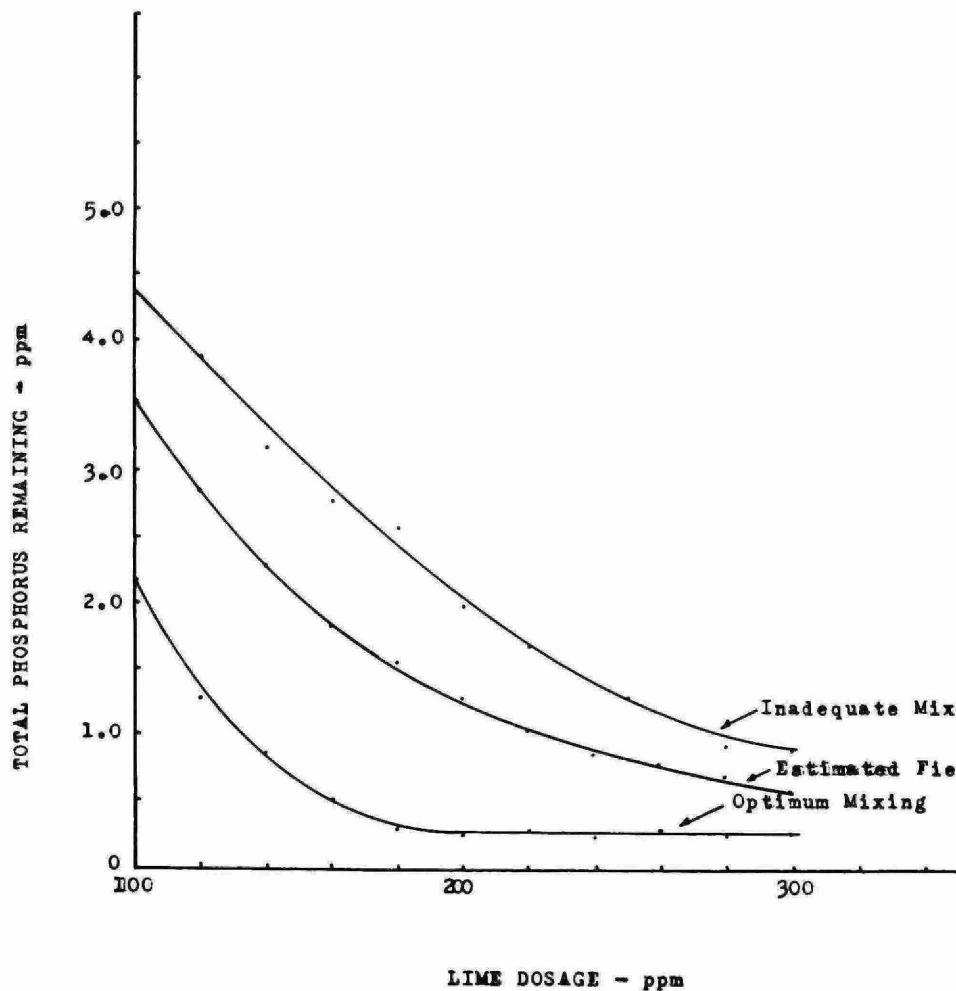
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FIGURE 4

Phosphorus Removal vs Lime Dosage

| SAB | | Nov. '69 |
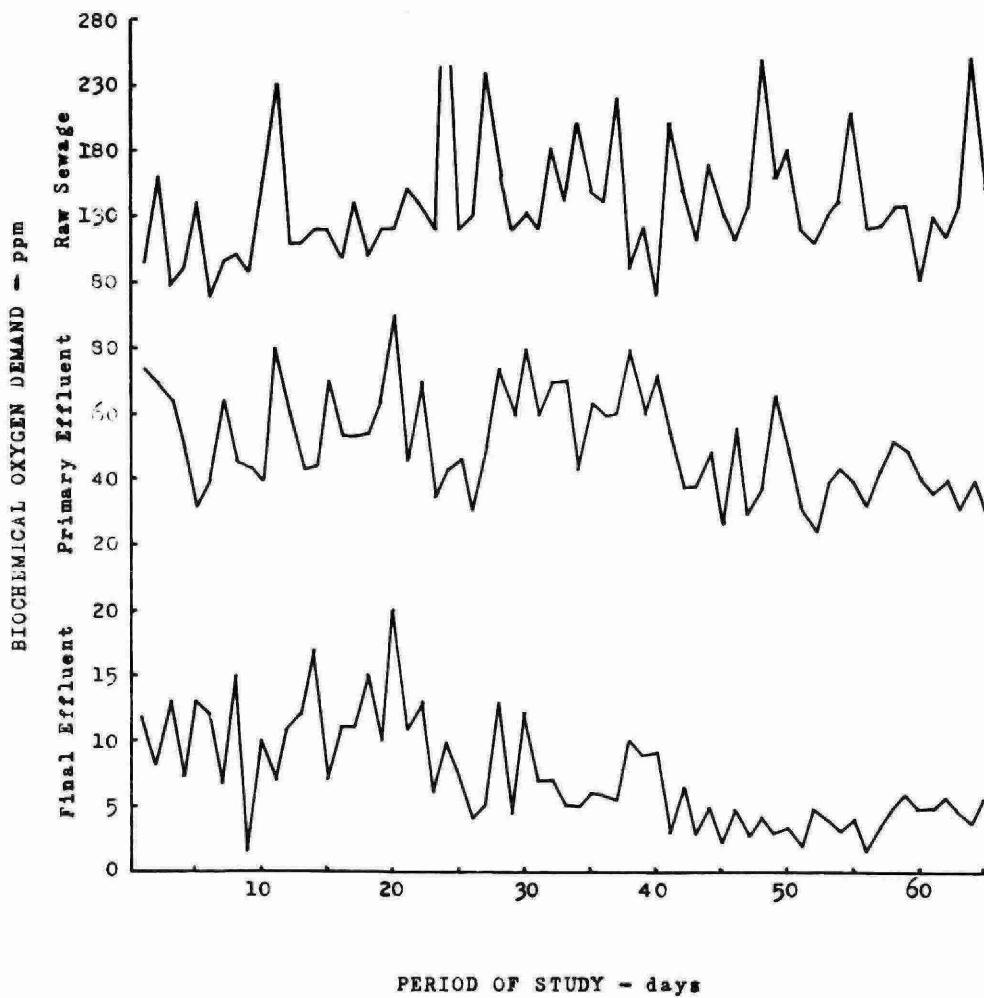
BIOCHEMICAL OXYGEN DEMAND — ppm

Raw Sewage

Primary Effluent

Final Effluent

PERIOD OF STUDY — days

PERIOD OF STUDY - days

- 24 -

PERIOD OF STUDY — days

TOTAL PHOSPHORUS AS P — ppm

Raw Sewage

Primary Effluent

Final Effluent
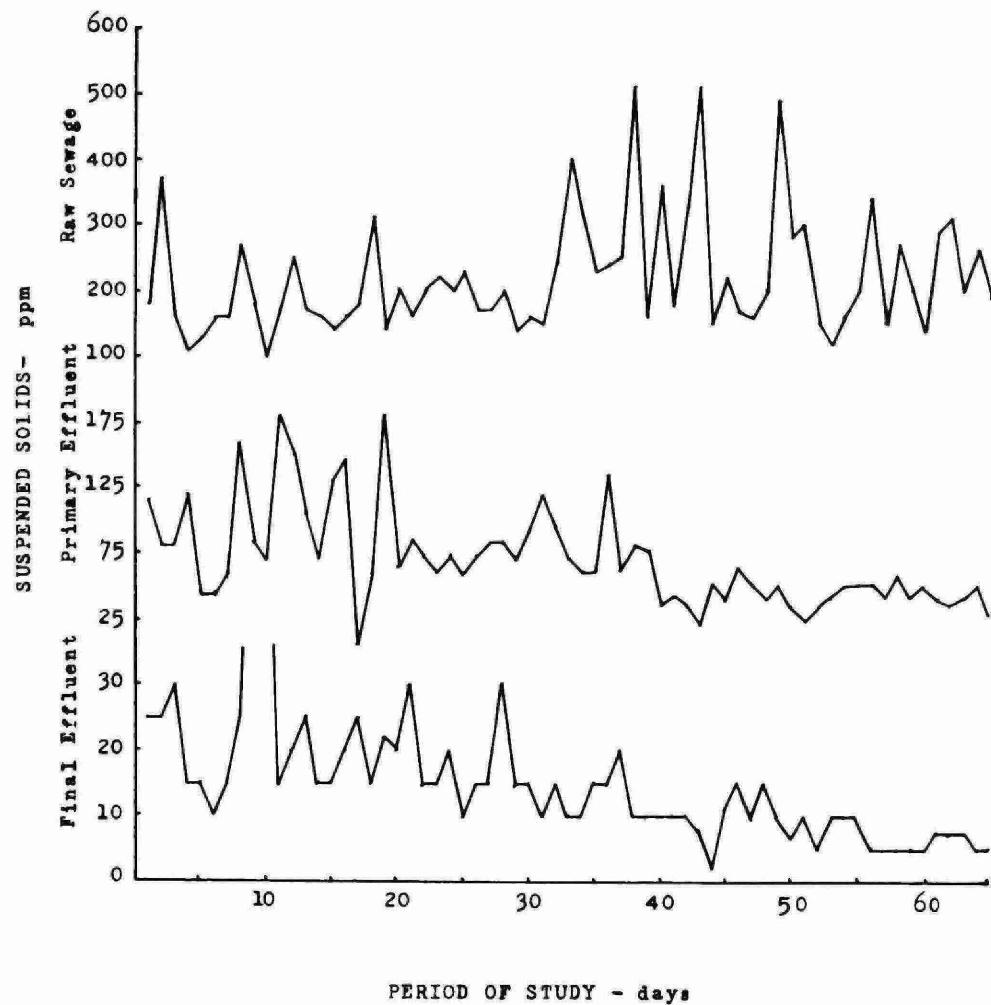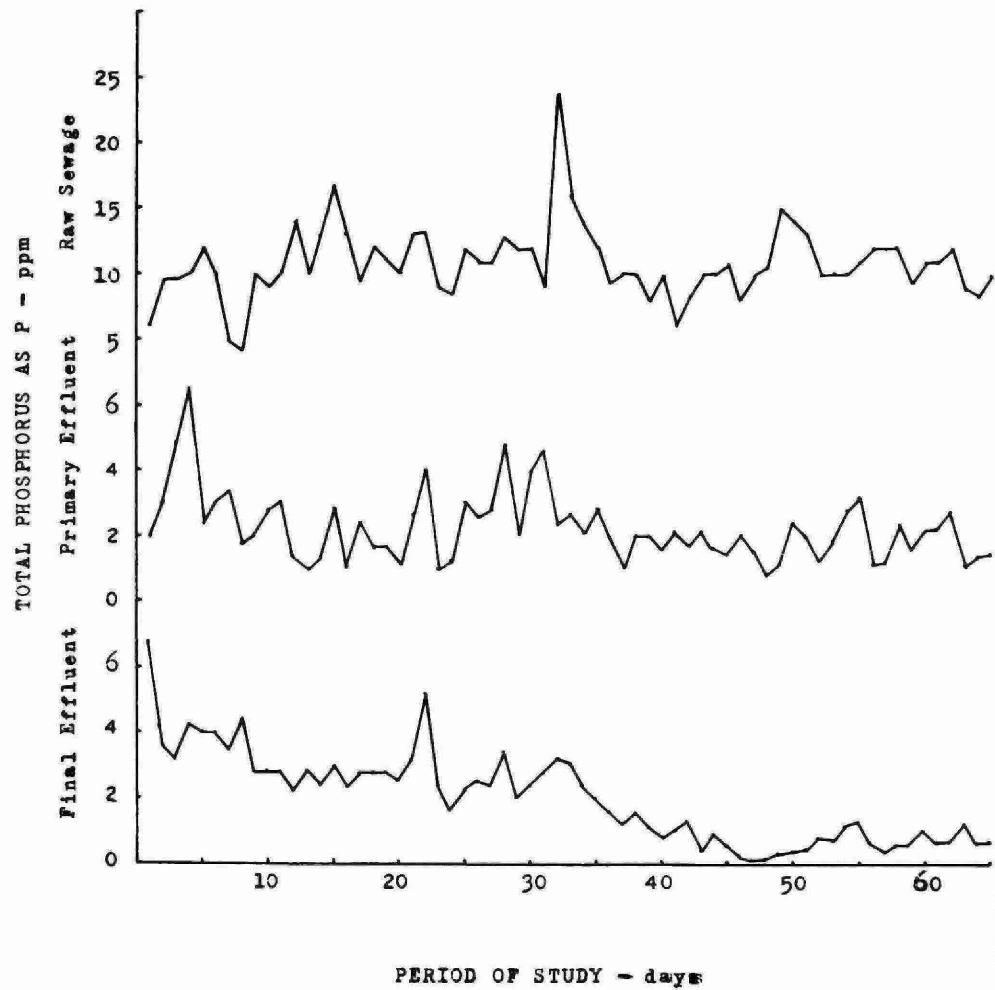
ONTARIO WATER RESOURCES COMMISSION DIVISION of RESEARCH		
FIGURE 7		
Total Phosphorus		
SAB		Nov. '69

PERIOD OF STUDY — days
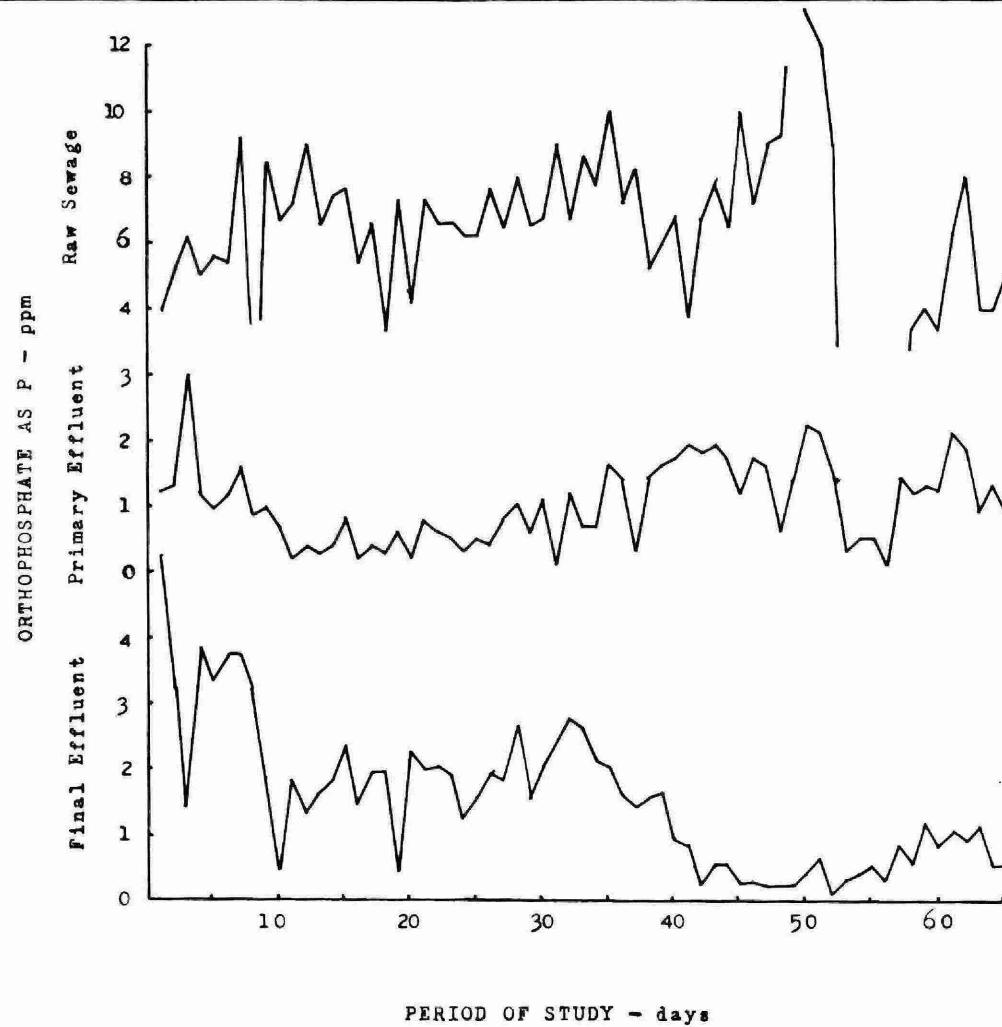
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FIGURE 8

Orthophosphate

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level began to drop and there was considerable difficulty in
reaching a stable level, and a period of about three weeks
elapsed until the suspended solids level returned to about
1,600 ppm where it remained until the conclusion of the con-
tinuous study. During this period of adjustment, many process
modifications were made in an effort to control the solids
level. The solids level of 1,600 ppm was reached only after
sludge wasting was discontinued and return sludge solids reached
a concentration of about 5,500 ppm. The air flow rate was also
reduced as much as possible but maintained such as to provide
adequate mixing.

During the restart phase of the study, a sludge
equilibrium was reached after 7 days and optimum treatment
achieved within two weeks.

During the study, a very deep brown sludge was de-
veloped indicating a healthy and active medium.

Other than causing the transformation within the
aeration mixed liquor solids content, the lime addition had no
detrimental effects on the secondary process. It had been thought
that the high pH of the primary effluent might affect the bio-
logical process, but it was found that this high pH was
immediately reduced by the free CO_2 in the aeration tanks. It
had also been throught that the low BOD of the primary effluent
might starve the biological process, and although it temporarily
appeared this way, a sludge equilibrium was reached and main-
tained throughout the remainder of the study.

By maintaining the design hydraulic loading, the
organic loading to the secondary process resulting from im-
proved primary efficiency, was such that the biological process
acted as an extended aeration system with no secondary sludge
being wasted for the final 6 weeks of the study. The F:M ratio
averaged 0.068 for the study.

It had also been thought that lime carryover might
eventually deteriorate the mixed liquor through a buildup of
calcium carbonate in the sludge. Figure 9 presents graphs of
percent volatile suspended solids of mixed liquor, and of
return activated sludge for the period of study. From these
graphs it can be seen that there was no buildup of lime
within the sludge even during the extended period of no sludge
wasting. This would indicate that there was little lime
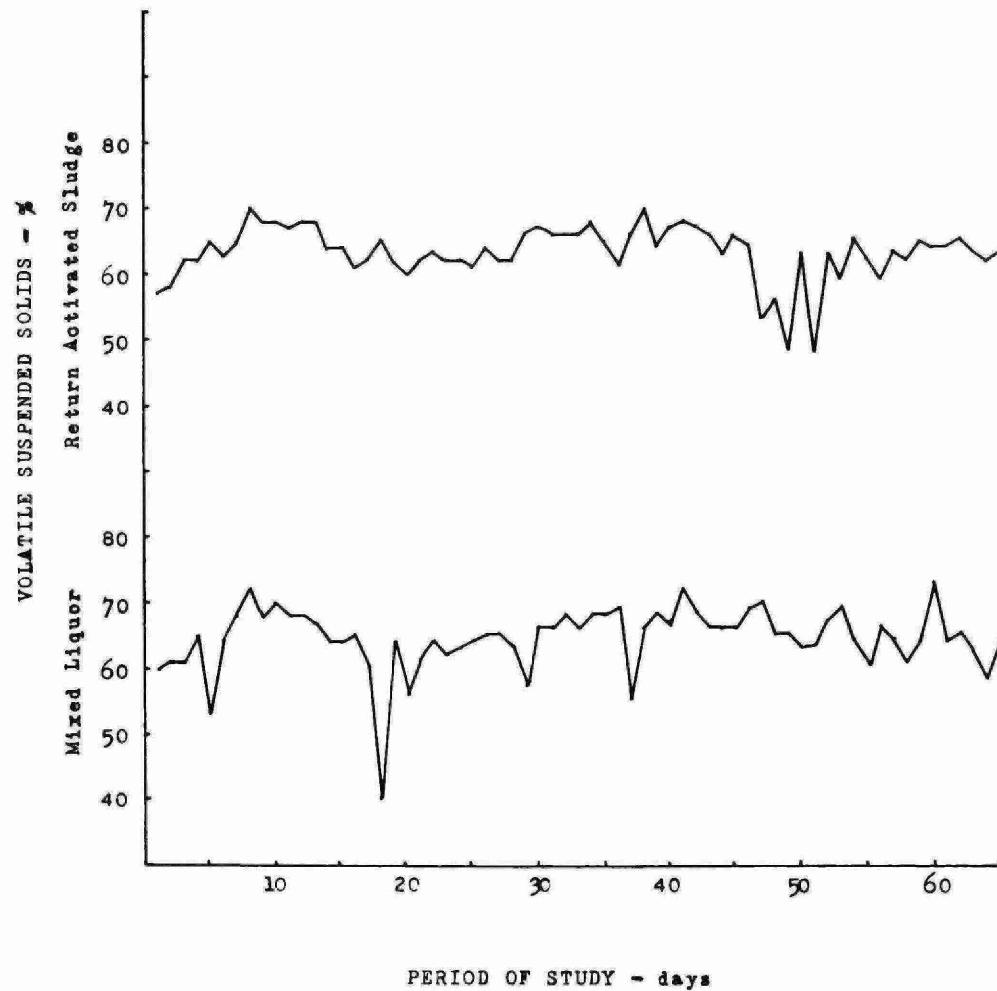
VOLATILE SUSPENDED SOLIDS – %

Return Activated Sludge

Mixed Liquor

PERIOD OF STUDY – days

carryover unless it settled out in the aeration tanks. Probing
of the tank bottoms however, indicated no solids deposition.
It would have been necessary to completely empty the tanks,
which was not practical at the time, to determine whether or not
a small amount of deposition had taken place. There was no
noticeable buildup on any visible piping or structures within
the aeration tank. Figure 10 further substantiates the fact
that the lime addition had no adverse effects on the aeration
process as the respiration rate remained relatively constant
throughout the study while the 30-minute settling test indi-
cated a slight increase in solids as is the case in any extended
aeration system.

Data for various parameters of the effluent from the
final clarifiers are presented in Table 3 and Figures 5 to 8.
As can be seen, the effluent contained very low BOD, COD and SS
concentrations compared to those expected from a conventional
activated sludge process. Total phosphorus concentration aver-
aged less than 1 ppm.

Phosphorus removal within the secondary process was
limited to 50% primarily because no sludge was being wasted.
The reduction which did occur, resulted from a gradual buildup
of phosphorus in the sludge. At the beginning of the study, the
aeration mixed liquor and return activated sludge averaged 35
and 110 ppm phosphorus, respectively. At the end of the 9½
week period the above sludges averaged 75 and 160 ppm phos-
phorus, respectively.

If the organic loading to the plant had been greater,
or if the aeration detention time had been decreased, sludge
wasting would have been required. This would have appreciably
increased the phosphorus removal within the secondary process.
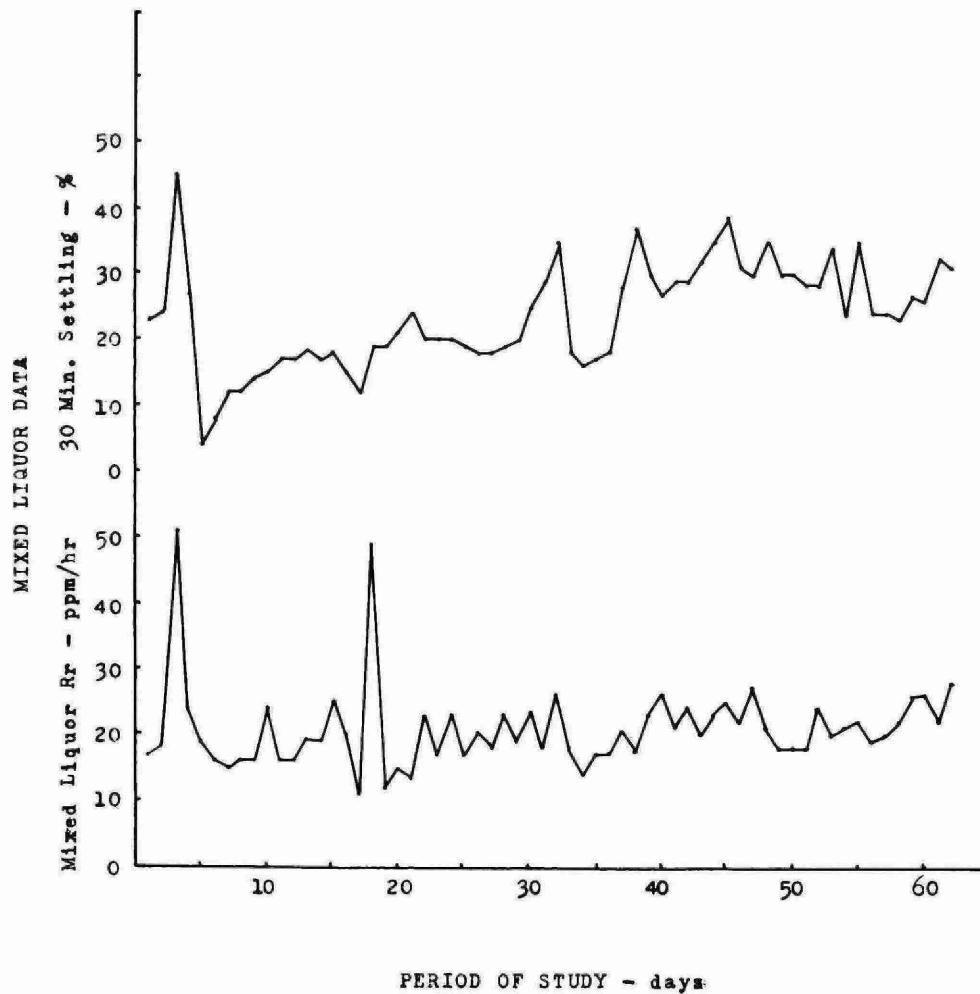
MIXED LIQUOR DATA

30 Min. Settling – %

Mixed Liquor Rr – ppm/hr

PERIOD OF STUDY – days

4.0 REACTIONS INVOLVED

1) Clarification Mechanism

        In the early era of sewage treatment when lime
treatment was practiced, clarification occurred through the
precipitation of calcium carbonate which acted as a coagulant
to the suspended organics. Because of the solubility relation-
ship of calcium carbonate, relatively large additions of lime
were required to cause the sufficient floc formation of calcium
carbonate resulting in the production of large volumes of
heavy sludge.

        With the advent of phosphorus-containing detergents
and the increased concentration of phosphorus in food stuffs,
clarification with lime occurs now through the precipitation
of calcium phosphate which acts as the coagulant. This is a
much more rapid reaction than was the precipitation of calcium
carbonate and occurs at a lower pH value and consequently re-
quires lower lime dosages with a resultant reduction in sludge
production.

        This precipitation reaction between calcium and
phosphorus occurs only with the orthophosphate forms of
phosphorus. Polyphosphates, of significant concentration in
raw sewage, are generally soluble and not amenable to actual
lime precipitation, but are apparently subject to quantitative
adsorption during suitable coagulation processes, significantly
increasing floc size and degree and rate of clarification.

        For a given sewage, a relationship may be established
between lime dosage, and resultant pH, and remaining phosphorus,
thereby establishing control requirements for optimum phosphorus
removal.

        Figure 11 presents graphs of lime dosage and remain-
ing phosphorus against final pH for the Richmond Hill sewage
under estimated field conditions. As can be seen, a pH value
in excess of 9.3 was necessary to achieve an effluent of less
than 1.5 ppm phosphorus.

        Similar graphs can be prepared from jar tests for
other raw sewages, thereby determining required lime dosages.
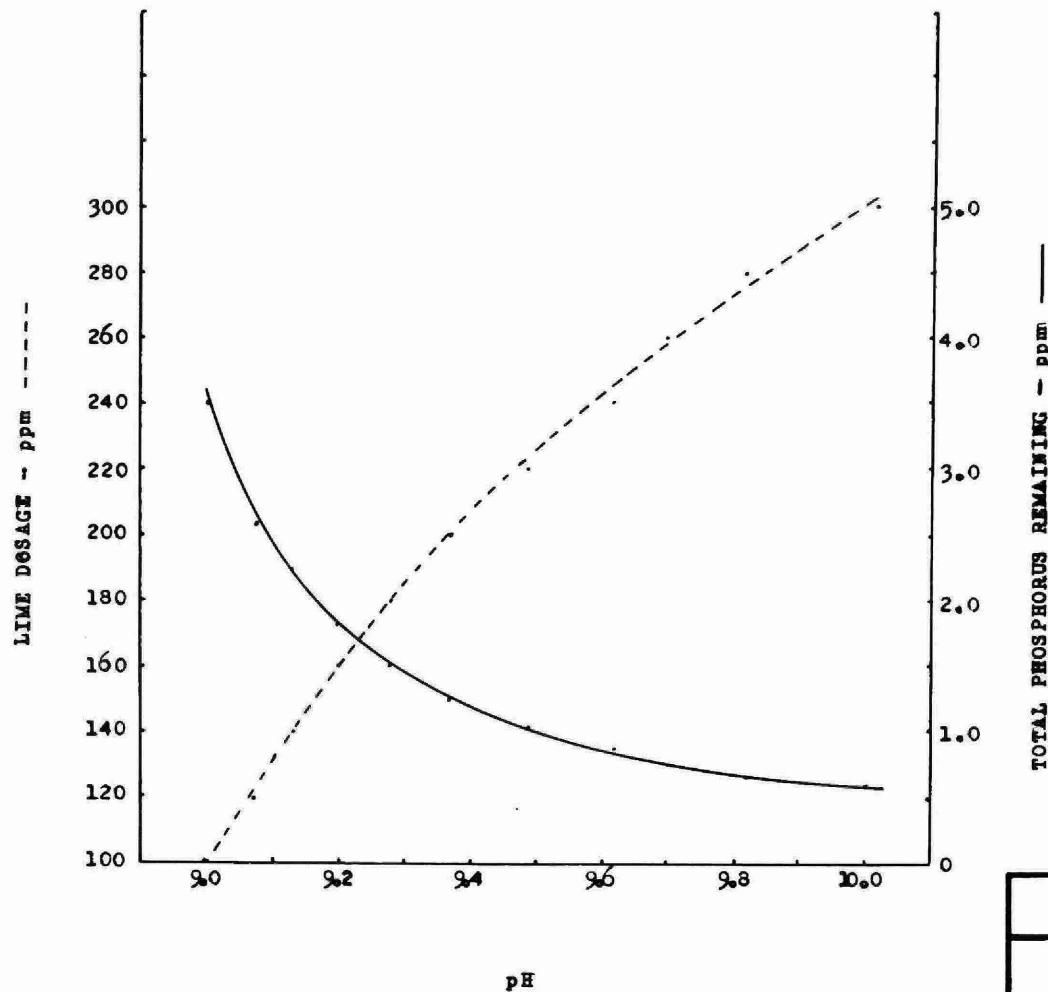
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FIGURE 11

pH vs Lime Dosage & P Removal

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2) Neutralization Process

As mentioned earlier in this report, the high pH of the primary effluent did not interfere with the biological process because of its immediate neutralization upon introduction into the aeration tanks. The high pH of the primary effluent was due to the carryover of $Ca(OH)_2$ which upon entering the aeration process, reacted with the CO_2 produced by bacterial respiration resulting in the formation of only slightly soluble calcium carbonate and/or soluble calcium bicarbonate. These reactions lowered the pH, in this case from an average of 9.2 in the primary effluent to an average of 7.8, in the aeration tanks.

5.0   CHEMICAL SLUDGE CHARACTERISTICS

The sludge precipitated in the primary clarifier
was a mixture of calcium phosphate, calcium hydroxide, calcium
carbonate and coagulated organics as well as the heavier grit
materials normally removed in primary treatment. The sludge
mixture in this case was considerably different from that
produced in the combined tank model plant, which was a more
gelatinous type sludge. That produced in this study was much
more free flowing and although it readily settled to a concen-
tration of 10 to 12% solids because of its bound water it was
very difficult to completely dewater.

The sludge was drawn off the primary clarifier at a
solids content of 6 to 8% and from several volume measurements,
was determined to be less in total volume than that produced
by conventional treatment.

The Richmond Hill study offered little opportunity
for investigating sludge handling and disposal methods. The
raw sludge is drawn off all four primaries into a common sump
and from there pumped to a two-stage anaerobic digester (See
Appendix). The contribution of chemical sludge was therefore
quite small compared to the total volume pumped to the digester.
Because of this, no attempt was made to determine the effects
of the lime sludge on the digester operation. No detrimental
or beneficial effects were apparent.

6.0   SLUDGE HANDLING AND DISPOSAL

The most difficult aspect of waste water treatment
today is the handling and disposal of sludges. Often it accounts
for 25 to 50% of the capital and operating costs of a sewage
treatment plant. From conventional treatment, raw sludge is
a semi-liquid with solids content ranging from 2.5 to 5% de-
pending upon the raw sewage composition. Waste activated sludge
contains from 0.5 to 1% solids and is much more difficult to
handle than the primary sludge. Activated sludges are also
very difficult to dewater.

Sludge handling and disposal practices have three
main objectives:

1)   to convert organic matter to a relatively stable
and odourless form,

2)   to reduce the volume of sludge by removing the
liquid portion and

3)   to destroy or control harmful organisms.

Because of the many digesters already located at
sewage treatment plants throughout Ontario, the question arises
as to whether or not the lime sludge is amenable to digestion.
There appears to be no practical value in attempting to digest
this sludge. Considering the three main objectives of sludge
handling and disposal practices as applied to the chemical
sludge, it was found from laboratory investigations that:

1)   The lime sludge is stabilized by the high con-
centrations of lime and is free from noxious odours even after
prolonged holding under anaerobic conditions.

2)   The chemical sludge can be thickened in a
thickening tank to in excess of 12% solids.

3)   The high lime content of the chemical sludge is
sufficient to destroy all coliform bacteria during prolonged
(4 weeks) holding.

If existing digesters are to be used for chemical
sludge handling they could serve as thickening and holding
systems for further disposal, for example wet haulage.

Although most of the agricultural land in Ontario is acidic in nature and its productivity would be enhanced by lime addition, allowable concentrations of lime sludge must be determined.

Other methods of sludge disposal include sludge thickening followed by vacuum filtration (conditioning with a polymer appears to be required) or centrifugation followed by sanitary land fill disposal. With sanitary land fill operation, the possibility of phosphorus release under lowered pH conditions would have to be considered.

Depending upon plant size and sludge disposal costs, it may be desirable to reclaim the lime. Although recovery and reuse of lime by recalcining in a multiple-hearth furnace is possible if the lime treatment follows secondary treatment (Culp, 1969), some question arises as to whether or not re-calcining of primary lime sludge is feasible (Schmid & McKinney, 1969 and Dorr-Oliver, 1967). Dorr-Oliver Inc. has indicated that lime sludge recalcination is possible in a fluid-bed reactor. Further research on lime recalcination is required.

7.0 EFFECTS OF VARIOUS FACTORS ON THE PROCESS

a) Hydraulic loading

From the results of this study, it would appear that
the hydraulic capacity of the process as adopted for an exist-
ing activated sludge plant is determined by the efficiency of
the final clarifier. During periods of flows of up to 150%
design through the test section, no noticeable detrimental
effects were observed on the primary clarifier or aeration
processes. At the higher limits however, floc carryover
occurred in the final clarifier. It was found that the addi-
tion of about 5 ppm $FeCl_3$ to the influent well of the final
clarifier relieved this situation, producing a well-clarified
effluent and also increasing the phosphorus reduction.

More research is warranted on determining minimum
primary detention times and aeration periods.

b) Organic loading

The results of this study indicate that the organic
capacity of an existing plant can be considerably increased,
without jeopardizing good treatment, through the addition of
lime to the primary clarifier.

Further studies will determine the maximum allowable
organic loading.

c) Raw sewage composition

The raw sewage at Richmond Hill contained a moderate
amount of industrial wastes which appeared to have no harmful
effects on the lime process. The effects of various industrial
wastes on the process should, however, be further investigated,
although there are few which would be expected to interfere
with the lime treatment. Perhaps laboratory tests would be
adequate for these determinations.

d) Sludge recirculation

The laboratory studies using the combined flocculation-
sedimentation system with high rates of sludge return, showed
that sludge recirculation increased the efficiency of the lime

and improved the effluent clarification. The set-up at
Richmond Hill would make sludge recirculation within the
primary fairly difficult, so no attempt was made to do this
even though it was realized that more efficient use would be
made of the lime.

e)   Thickening tank supernatant return

If a thickening tank were used in sludge handling,
the supernatant would be returned to the raw sewage. This
would partially achieve the effects of sludge recirculation.
It was found that even after 5 weeks of retention, the super-
natant from the chemical sludge contained no appreciable
amounts of phosphorus, either total or soluble.

8.0 PROCESS CONTROL

Lime addition should be controlled so as to maintain an optimum phosphorus removal level, as determined from laboratory investigations on the waste under consideration, and from initial operational experience at the plant. Since diurnal fluctuations in sewage flow always occur, a direct control of the chemical feed rate to the flow should be established. This could be accomplished through a flow controlled system controlling the chemical feed directly to the flow variation or through a pH control on the flash mix or primary effluent. Feed control of lime would be much simpler than that of a chemical dependent upon incoming phosphorus concentration.

9.0   EQUIPMENT REQUIREMENTS

One principal advantage of this process over the more conventional tertiary treatment process is that the duplication of existing facilities is not necessary. Additional equipment will include lime storage, lime feeding and process control facilities. It may prove advantageous to include flash mixing and sludge recirculation facilities but the existing primary clarifier can be used to provide flocculation and sedimentation detention.

The lime process, in addition to greatly reducing the phosphorus concentration of sewage, will provide additional capacity to the primary and aeration facilities of existing plants which may be of considerable benefit in organically overloaded situations, or where plant expansion is being contemplated.

10.0 APPLICABILITY OF LIME TREATMENT PROCESS

This process was developed in order to convert existing sewage treatment plants to phosphorus removal processes. Before this process is considered at a particular location, it must therefore be determined whether or not phosphorus removal would be beneficial to the receiving water.

The process described herein is based upon the use of lime as the chemical precipitant responsible for the removal of phosphorus. Other chemicals could also be used. Factors to be considered in the choice of chemical include cost, quantity required, handling, storing and feeding requirements, effectiveness in producing desired results and type of sludge produced. Based upon laboratory investigations and this demonstration project, it is felt that lime will be the most economical chemical for extensive use throughout Ontario. Each installation however, must be considered on an individual basis.

11.0   SIDE BENEFITS OF LIME TREATMENT

The use of lime addition to the primary clarifier
of a conventional activated sludge plant has many side benefits
in addition to the purpose for which it was developed, namely,
for phosphorus removal. Some of these benefits, increased
hydraulic and organic capacity, increased efficiencies in BOD
and SS removals, reduced cost of aeration, have already been
mentioned. Other benefits include better oil, grease and
scum removal in the primary clarifier, prevention of corrosion
in sludge pipes and also of considerable importance, the con-
version of all forms of nitrogen to the nitrate form which
may be removed from the final effluent if so desired by a
single tertiary step. As can be seen from Table 3 the total
Kjeldahl nitrogen of the final effluent averaged only 1.2 ppm.
This conversion is believed to be the result of the decreased
organic loading and resultant high oxygen content (average of
2 ppm) in the final effluent.

12.0 PROCESS MODIFICATIONS TO INCREASE EFFICIENCY

During the course of this investigation, certain process modifications for increasing the efficiency of the lime treatment process over that achieved by the Richmond Hill study, became apparent.

Of prime importance to achieving optimum results is the adequate control of the lime feed. Ideally, the lime would be fed with the raw sewage into a flash mixing tank of 3 to 5 minutes detention. The lime feeding pump could then be directly controlled by the pH of the effluent from the mixing tank. The flash mixer would also ensure adequate mixing of the lime with the raw sewage as the adequacy of mixing within the raw sewage inlet channel at the Richmond Hill WPCP was questionable.

To increase the efficiency of phosphorus removal during the secondary treatment stage, the aeration volume capacity should be decreased such that a high organic loading is maintained, necessitating the continuous wasting of sludge and thus permitting the removal of phosphorus from the system. Such modifications may be readily achieved in plants with multiple aeration tanks.

The effects of wasting secondary sludge to the primary clarifier or raw sewage inlet as well as the effect of the combined waste sludge on digester operation, requires further investigation. It appears that sludge wasting to the point of lime application may be beneficial to primary treatment efficiency in providing additional floc material.

As determined during the laboratory studies, sludge recirculation improves the efficiency of the lime, reducing the dosage requirements and also improves the clarification of the process. If sludge recirculation could be incorporated into the process, it would significantly reduce chemical requirements.

13.0   CONCLUSIONS

The study at the Richmond Hill WPCP demonstrated
that high levels of phosphorus removal from raw sewage are
possible through the addition of moderate levels of lime to
the influent channel of the primary clarifier of an existing
conventional activated sludge plant. Other benefits of the
lime addition include increased organic capacity of the entire
plant process, increased hydraulic capacity of the primary
clarifiers and aeration process, increased overall efficiencies
in BOD and SS removals as well as better oil, grease and scum
removal in the primary clarifier.

With improved methods of lime feeding and control,
the efficiency of a permanent installation of the process
would be superior to those obtained in this study.

Although there are several aspects of this process
that require further investigation, its basic principals have
been established, making a permanent installation of the pro-
cess now feasible. In order to be successful however, such
an installation must provide for adequate control of lime
dosage, either through flow or pH monitoring.

The type of sludge produced lends itself to thicken-
ing and wet haulage for disposal. It is fairly stable,
producing no appreciable odour after prolonged storage, can be
readily thickened to in excess of 10% solids, and in this case,
contained no living coliform bacteria after 4 weeks of storage.
It is not felt that the chemical sludge will augment present
sludge handling and disposal problems, but may lead to a
change in methods.

At this time, the cost of this phosphorus removal
process can only be estimated. Capital costs will include
lime storage, handling, feed and feed control equipment, as
well as perhaps a modification of sludge handling and disposal
facilities. Additional operating expenses will involve
primarily the cost of the lime. These costs will be consider-
ably, if not completely, offset by savings in secondary process
operating costs, and in improved effluent quality.

ACKNOWLEDGEMENTS

REFERENCES

Alarcon (1961), "Removal of Phosphorus from Sewage", Master's Thesis, The John Hopkins University, Baltimore, Md.

Bebin (1968), Formal Discussion, Section 111, Paper 1/Popel, 4th Int. Conf. on Water Poll. Res., Prague 2-6, Sept.

Bogan (1961), "The Use of Algae in Removing Nutrients from Domestic Sewage", In "Algae and Metropolitan Wastes", U. S. Public Health Service, Cincinnati, Ohio.

Culp, (1969), "The Status of Phosphorus Removal", Public Works, October.

Culp & Mayer (1969), "Wastewater Reclamation and Export at South Tahoe", Civil Engineering, Vol. 39, June.

Dorr-Oliver Inc. (1967), "Phosphate Extraction Process", Paper presented at the Pacific Northwest Section meeting of the WPCF of Yakima, Washington, Oct. 25-27.

Eberhardt & Nesbitt (1968), "Chemical Precipitation of Phosphorus Within a High Rate Activated Sludge Process", Publication by The Pennsylvania State University, Dept. of Civil Engineering, Sanitary Engineering. Laboratories, March.

Ericsson & Westberg (1966), "Lowering the Phosphorus Content at Waste Disposal Plants", Tek. Tidskr. (Sweden), 96.

Feng (1962), "Phosphorus and the Activated Sludge Process", Water and Sewage Works, 109.

Harris (1957), "Radiophosphorus Metabolism in Zooplankton and Microorganisms", Can. Jour. Zool., 35.

Jenkins & Menar (1968), "The Pathways of Phosphorus in Biological Treatment Processes", Paper presented at the 4th Int. Conf. on Water Poll. Research, Prague, 2-6 Sept.

Lea & Nichols (1936), "Influence of Substrate on Biochemical Oxygen Demand", Sewage Works Journal, 8.

OWRC, Division of Research Paper 2004, "Phosphorus Removal by Algal Culture".

Popel (1968), "Phosphorus Removal with Ferric Iron and Aluminum", Paper presented at the 4th International Conference on Water Pollution Research, Prague, 2-6 Sept.

Sawyer (1944), "Biological Engineering in Sewage Treatment", Sewage Works Journal, 16, 9, Sept.

Sawyer and Buzzell (1966), "Removal of Algal Nutrients From Raw Wastewater With Lime". JournalWPCF, October, 1967.

Schmid & McKinney (1969), "Phosphate Removal by a Lime-Biological Treatment Scheme", Journal WPCF, July.

Shapiro & Levin (1965), "Metabolic Uptake of Phosphorus by Wastewater Organisms", Journal, WPCF, June.

Srinath, et al (1959), "Rapid Removal of Phosphorus from Sewage by Activated Sludge", Experientia, 15.

Tenney & Stumm (1965), "Chemical Flocculation of Micro-organisms in Biological Waste Treatment", Journal WPCF, 37.

Thomass (1966), "Phosphate Precipitation in the Clarification Plant at Uster and the Removal of the Iron-phosphate sludges", Naturforschende Gesellschaft Zurich 111:309-318.

Vacker, et al (1967), "Phosphorus Removal Through Municipal Wastewater Treatment at San Antonio, Texas", Journal WPCF, Vol. 39, No. 5.

Weinberger (1968), Statement on "Waste Treatment for Phosphorus Removal", at the Lake Michigan Enforcement Conference, February.

WPCF (1959), "Sewage Treatment Plant Design", WPCF Manual of Practice No. 8.

Wuhrmann (1957), "Tertiary Treatment", Schweiz., Z. Hydrol.,19.

Wuhrmann (1968), "Objectives, Technology and Results of Nitrogen and Phosphorus Removal Processes", Advances in Water Quality Improvement, Water Research Symposium #1, Edited by Gloyna and Eckenfelder, Jr.

APPENDIX

RICHMOND HILL WATER
POLLUTION CONTROL
PLANT

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